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A PHYSICALLY BASED ANALYTICAL MODEL
FOR PREDICTING HTGR CORE SEISMIC RESPONSE

by

Joel G. Bennett

ABSTRACT

An analytical model is described that was developed to predict the seismic response of large High Temperature Gas-Cooled Reactor cores. Applications of the model are listed and discussed.

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INTRODUCTION

An important requirement of HTGR safety research is to assure the integrity of an HTGR core during seismic excitation. To meet this objective it is necessary to be able to predict the forces and motions of the various core elements under potential upset conditions.

The system of loosely stacked graphite blocks that makes up the core of the HTGR presents an unusual structural problem. Each one of the several thousand blocks has the kinematic capability of undergoing three translations and three rotations, therefore requiring six independent coordinates for a complete description of the motion. Resulting deformations and stresses are dependent upon graphite material properties that are known to vary with time, temperature, radiation level, and loading history. It is apparent from the complexity of both material properties and geometries that any analysis of this system requires a number of simplifications. It is especially important that any analysis be designed to allow as complete validation as is possible of simplifications made and methods used. Assumptions regarding the general motion of the system, the mechanism of energy loss, the properties that govern system behavior, etc., should not be made intuitively. Rather, analytical and experimental models should be first designed for the specific purpose of determining permissible assumptions and the validity of methods that can later be applied to the analysis of the HTGR core.

THE PHYSICALLY BASED MODEL

By a physically based model we mean an analytical model that doesn't necessarily bear any resemblance to the HTGR core, but that does maintain all important governing physical parameters that will affect the seismic response of the core. Furthermore, the model has a well defined physical counterpart that is both economic and simple to use for experimental verification studies.

Figure 1 is a free-body diagram of a core block for our model showing the forces that are allowed to act upon it. A number of these blocks are then arranged in one-or two-dimensional arrays and subjected to one or two independent motion-time inputs. Figure 2 illustrates a two-dimensional array.

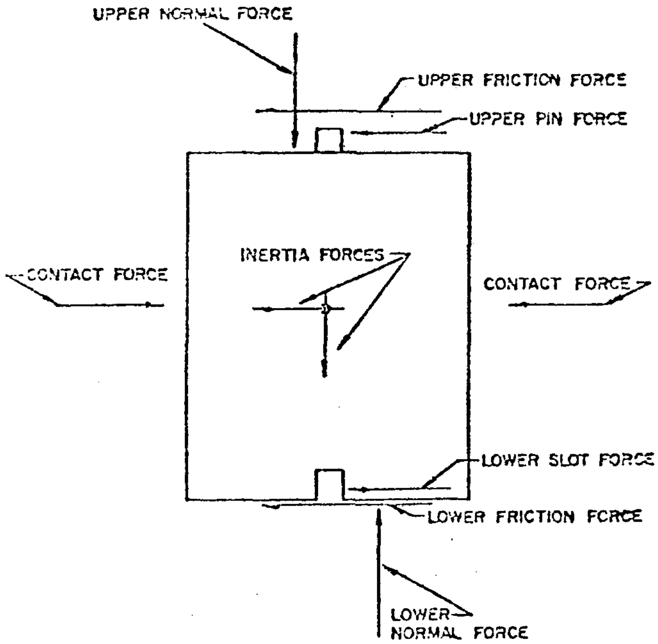

Fig. 1 Forces acting on core block

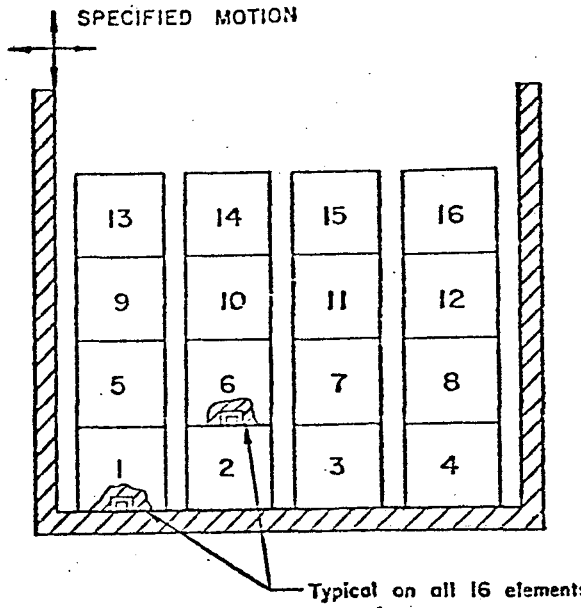

Fig. 2 Two-dimensional model

A significant difference between this model and the usual structural model is that it uses Coulomb friction rather than viscously damped spring-masses.

THE EQUILIBRIUM-ITERATION SCHEME

The equations of motion governing the system are solved numerically using a typical equilibrium iteration time history scheme.

A flow-chart of the equilibrium-iteration scheme is shown in Fig. 3. The method is a time-history approach that traces each mass through a succession of equilibrium configurations. Each succeeding configuration is based on the preceding state, i.e., the preceding equilibrium state is used as a set of initial conditions for the new state.

Referring to Fig. 3, it should be noted that the boundary conditions must be known functions of time for input to this program. These can be either analytic functions or time-histories. This step presumes that the core response can be decoupled from the motion of the Prestressed Concrete Reactor Vessel (PCRV). This is a reasonable assumption since the mass of an actual HTGR core is less than one-tenth that of the PCRV. A separate lumped mass analysis would supply PCRV motion for input to this code. However, this is not a necessary step for determining the influence of parameters on core response.

The Newmark β method with $\beta = \frac{1}{4}$ is used to integrate the equation of motion in step 3 of Fig. 3.[1]

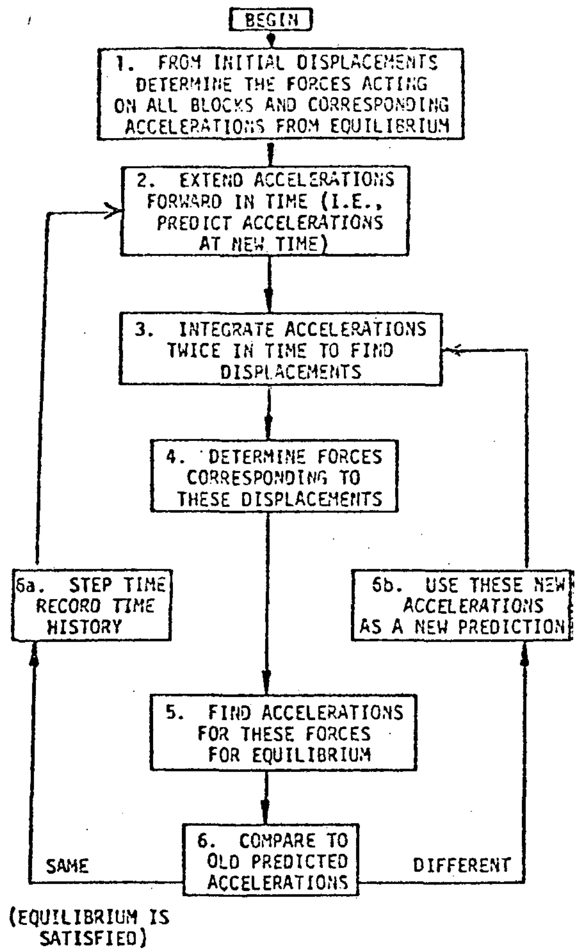

Fig. 3 Equilibrium iteration scheme

BLOCK STIFFNESS, FRICTION AND INTERNAL DAMPING REPRESENTATION

Stiffness Representation

Figure 4 shows typical force-displacement curves for side contact forces that might be used in step 4 of Fig. 3. In the literature the technique used is known as the component element technique. As many components as desired may be attached to a given mass to represent separate effects. The curves in Fig. 4 give the force component due to a spring element with the force displacement characteristics shown.

Information for these curves can be obtained from other analyses and Ref. 2 describes one method of using the finite element technique that can be extended to blocks made of nonlinear materials. For linear problems an equivalent spring can be found from the reduced stiffness matrix derived by inverting the flexibility matrix found from applying unit loads to each node on the contact face of the finite element representation of the block.

The component element concept as applied in our physically based model includes force components due to side and vertical contact forces with hysteretic energy loss, pin-slot contact forces, and frictional forces.

The Friction Model

The friction model implemented in our physically based model is illustrated in Fig 5 and is the type generally presented in elementary particle mechanics courses.

First, a decision is made based on the relative velocity between the contact surface and the block. If relative velocity exists, the frictional force applied to the block opposes the relative velocity in sign and is $\mu_k F_N$ in magnitude, where μ_k is the kinetic coefficient of friction and F_N is the normal force at the contact surface.

If no relative velocity exists between the contact surface and block, the no-slip condition exists, and the block and contact surface accelerations are the same. For example, referring to the free body diagram in Fig. 5, the friction force necessary for dynamic equilibrium is given by

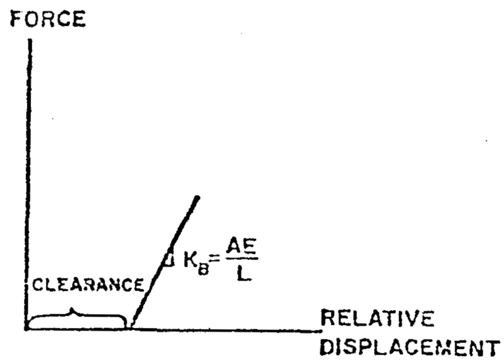

Fig. 4a Typical force displacement curve for bi-linear model

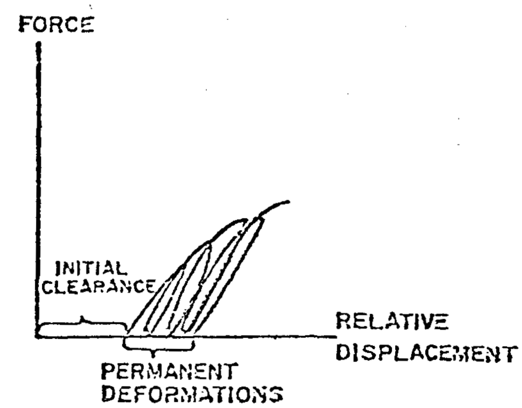

Fig 4b Typical force displacement curve for non-linear model

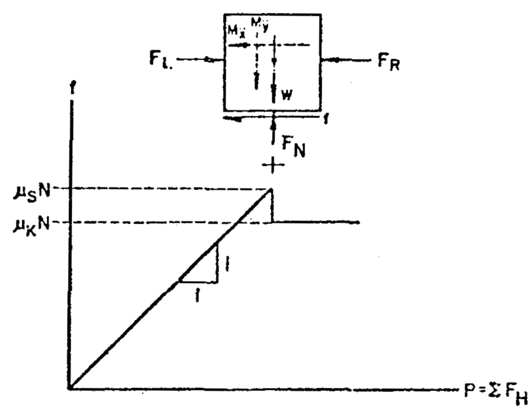

Fig. 5 Proportional frictional force model

$$f = M\ddot{X}_B + F_R - F_L, \tag{1}$$

where $\ddot{X}_B$ is the contact surface or base acceleration, and F_R and F_L are right and left side contact forces. The force calculated from this expression is compared to the breakaway value given by $f_{max} = \mu_S F_N$. For a time-varying normal force, this breakaway value is computed each time step and the current value is used in this comparison. If f is greater than f_{max}, then the block is breaking away and f_{max} is applied to the block for this time step; otherwise, the computed f from Eq. (1) is used. This model works well and is believed to give an accurate representation of the physical process.

As described and shown in Fig. 5, the model for one contact surface has been extended and used in our two-dimensional array core of Fig. 2, where frictional effects on top and bottom surfaces are represented in a similar manner.

THE MATERIAL HYSTERESIS LOSS MODEL

The use of a material hysteresis loss model is an attempt to represent the effect sometimes expressed by a coefficient of restitution, i.e., energy is lost, but momentum is conserved during impact. It is also based on the hystersesis loop obtained in the loading-unloading stress-strain test for nonlinear materials such as graphite.

Figure 6 illustrates the material hysteresis loss model used in our analysis, with the shaded area of the hysteresis loop representing mechanical energy lost during the loading-unloading impact sequence. The sign of the relative velocity of the two impacting masses is examined to determine if a block is being loaded or unloaded. If loading is occurring, the force acting on the block is given by

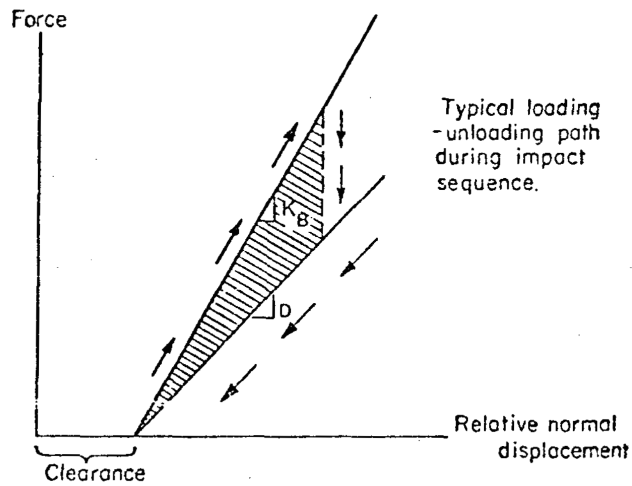

Fig. 6 Force-displacement curves for the material hysteresis energy loss model.

the upper curve; whereas if unloading is occurring the force is given by the lower curve. The slope of the lower curve is determined by specifying the percentage energy loss during the impact sequence. Thus,

$$D = K_B - \frac{\%E\ \text{loss}}{100}\ K_B, \qquad (2)$$

where

D = slope of the unloading curve,

E = elastically stored energy, and

K_B = block stiffness.

A more realistic nonlinear description of the hysteresis loss can be used if desired, with a mathematical description of the loading and unloading curves. The advantage of the model used here is its simplicity and ease of implementation. The disadvantage is that the model does not account for any accumulating permanent deformation.

For a detailed discussion of the analytical model the reader can consult Refs. 2, 3, and 4.

APPLICATIONS OF THE MODEL

A number of useful studies have been made using the analytical model and we summarize them as being in the following catagories.[5,6,7]

- o A computer built scale model study was performed to check scaling laws. The use of a computer model allows a choice of material properties, including ones for which no real material can be found.
- o A parameter study was performed where physical and geometric properties and the excitation function were varied to gain greater understanding of the physical system.
- o System response to various mixed frequency inputs was studied.
- o System response to random excitation was examined.
- o System damping effects were studied.

A few of these applications are summarized below.

Parameter Study

A parameter study was conducted in terms of the dimensionless Pi terms that were derived from a similitude analysis.[5] One of the first investigations was made of a one dimensional system using only the bottom row of blocks in Fig. 2 and eliminating the pin-slot forces. The functional equation for such a system can be shown to be

$$\frac{\ddot{X}}{g} = \Psi\left(\frac{X_B}{d}, \frac{c}{d}, \frac{Ed^2}{W}, \mu_k, \frac{\mu_s}{\mu_k}, \frac{E}{D}, \frac{X_B}{gt^2}\right) . \tag{3}$$

where

$\ddot{X}$ = acceleration of a block

X_B = amplitude of motion applied to the base

t = period of input motion or any significant time

d = characteristic block dimension

c = clearance between blocks

W = weight of block

μ_s = static coefficient of friction

μ_k = kinetic coefficient of friction

E = modulus of block, loading

D = modulus of block, unloading

g = gravitational constant.

The first study was to determine the effect of varying static friction (breakaway friction) μ_s. The variation in μ_s was found to have little effect on the block accelerations provided that the exciting force is large enough to insure that the blocks do breakaway. As a result of this finding, static friction (μ_s) may be eliminated as an independent governing parameter. Figure 7 shows the great importance of the clearance gap (c) on block acceleration. The effect of varying the coefficient of kinetic friction (μ_k) is shown in Fig. 8. The importance of the kinetic friction effect in limiting acceleration is clear.

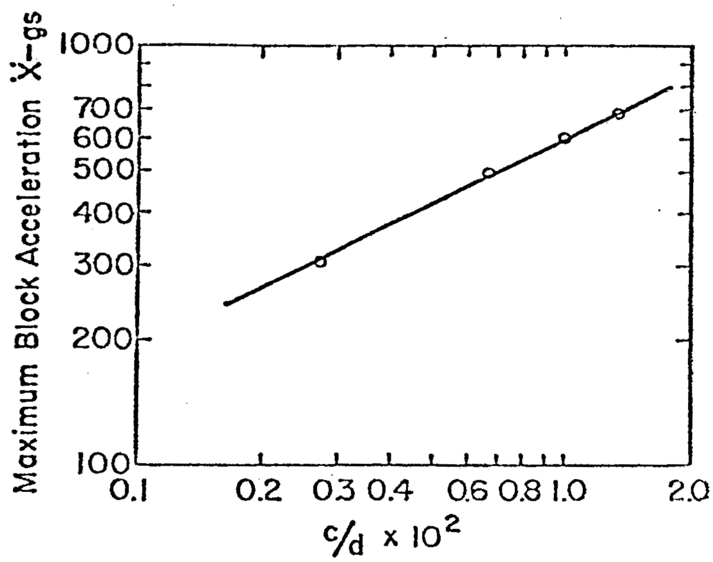

Fig. 7 Effect of clearance gap

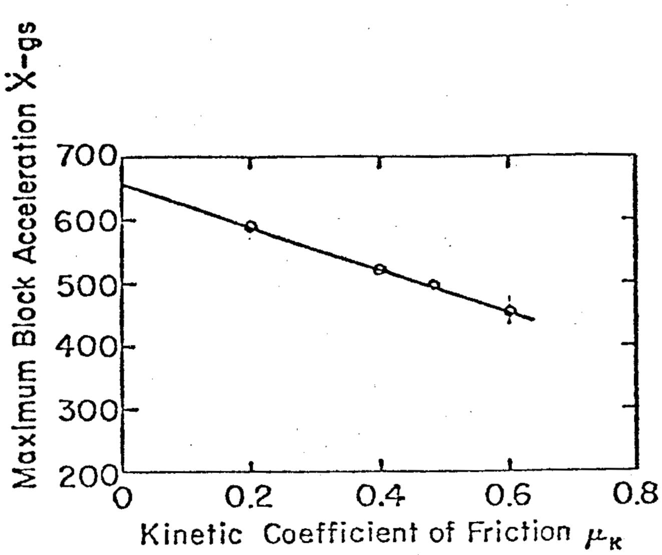

Fig. 8 Effect of kinetic coefficient of friction

The effect of energy loss due to inelastic impact was studied by varying the ratio (e/D). The effect of internal energy loss on block accelerations is relatively small.

From the functional equation it can be seen that the effect of block stiffness (E) and block weight (W) can be investigated simultaneously. The results of this investigation are shown in Fig. 9

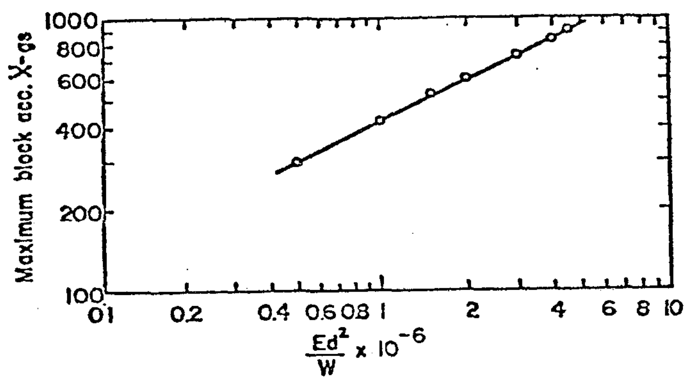

Fig. 9 Effect of modulus to weight ratio

The analytical model has also been applied to the two-dimensional system (Fig. 2) to investigate the effect of the core blocks' pin connections.

A series of computer runs were made in which pin clearance and pin stiffness were varied. The results may be summaried as follows:

1. Side contact between blocks is eliminated in all horizontal rows below which the accumulated pin gap clearance is less than the gap between blocks.
2. Smaller pin-slot clearances produce more numerous, but less intense pin/slot impacts.
3. Stiffer pins produce more numerous and more intense pin/slot impacts.

The model was also used to investigate response when the system is simultaneously excited by horizontal and vertical acceleration-time histories from simulated earthquake records. The accelerograms selected for the excitation produced response spectra that enveloped the Nuclear Regulatory Commission guide 1.60 response spectra for a 1 g earthquake with 0.5% damping.

When the model is simultaneously excited by horizontal and vertical acceleration-time histories, the horizontal response is different than for the case of horizontal excitation only because the vertical input causes time variations in the normal forces (and, hence, the friction forces) between the horizontal surfaces of the blocks. However, this coupling of vertical input to horizontal response has a small effect on peak block acceleration. The vertical response of the blocks within the system is identical to that produced by vertical excitation only. The model was designed with zero friction between the vertical surfaces of the blocks and, hence, there is no coupling of horizontal input to vertical response.

The vertical response accelerations were surprisingly large in view of the fact that there is no initial gap between the blocks as they are stacked vertically. However, the model indicates that the blocks do separate even when the vertical excitation is of low magnitude if the excitation contains high frequencies.

Some general conclusion can be drawn:

1. Vertical accelerations and forces (which are due exclusively to vertical input in this model) are larger than were anticipated. High-frequency excitation causes the blocks to separate and impact against each other. In this regard, it must be remembered that the model (Fig. 2) does not include any vertical hold-down mechanism.

2. The effect of vertical input on horizontal response appears to be relatively small but random,

3. The variation in normal forces produced by the vertical input result in numerous horizontal acceleration pulses of small amplitude, that is, the vertical excitation results in jerky horizontal motion.

SYSTEM DAMPING

Computer runs in which the exciting force was suddenly reduced to zero indicate that with reasonable values of coefficient of friction, the effective damping is large in this system. Figure 10 shows the acceleration-time response for block #1 when the system was driven with a $\pm$ 1 g, 5-Hz, excitation for 0.4 sec (two cycles), after which the excitation was reduced to zero. As shown in Fig. 10, where the value of the kinetic friction (μ_k) is 0.16, block impacts cease very soon after the excitation goes to zero.

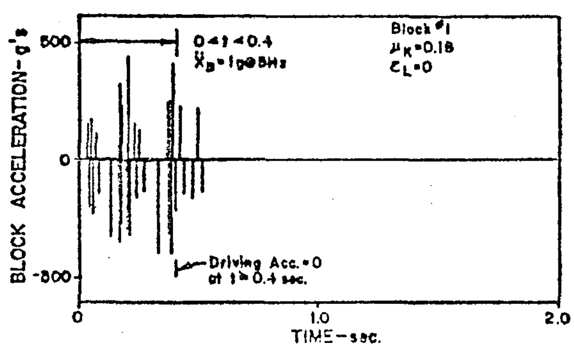

Fig. 10 Effect of Coulomb damping

In this computer run the material hysteresis loss during impact (E_L) was set at zero. The run was repeated setting the kinetic frictional coefficient to zero and with a substantial 40% energy loss during impact. The same large effective system damping was observed. Recent physical tests conducted on a physical model of this system also indicate high damping. This indication of large effective damping means that the system has little memory of past acceleration-time history. Therefore, for some purposes both the analytical and experimental models may be appropriately driven using only selected abbreviated portions of a simulated earthquake time history. An exception to this is when the total number of block collisions is desired (as for a fatique damage study), rather than maximum values of accelerations or forces.

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